Ref.TH.2836-CERN

HIGH TRANSVERSE MOMENTUM PION AND PHOTON PRODUCTION
IN pp COLLISIONS AT ISR ENERGIES

R.R. Horgan
CERN - Geneva

and

P.N. Scharbach
Niels Bohr Institute - Copenhagen
and
Rutherford Laboratory - Chilton, Didcot

A B S T R A C T

High transverse momentum (p_T) production of pions and prompt photons in proton-proton collisions is studied in a QCD model including "higher twist" contributions parametrized by the Constituent Interchange Model. QCD scaling violations are included and comparisons are made with ISR data on invariant cross-sections and the γ/π^0 ratio. Studies of the away-side jet and charge angular distributions are proposed in order to isolate the various subprocesses contributing to high p_T production, in particular that involving the trigluon coupling of QCD.

1. INTRODUCTION

In the past few years, Quantum Chromodynamics (QCD) has developed a strong claim as the basic field theory of strong interactions¹⁾. Its property of asymptotic freedom²⁾ and the factorization theorem³⁾ render perturbative calculations meaningful in the domain of large momentum transfers and allow the application of parton model ideas to the hard scattering constituent subprocesses of lepton-hadron and hadron-hadron scattering. In particular, attempts have been made⁴⁾ to understand the large transverse momentum (p_T) behaviour of hadron-hadron collisions as reflecting the wide angle scattering of fundamental quark and gluon fields governed by the non-abelian dynamics of QCD. The change in the p_T power behaviour of the π^0 inclusive cross-section studied by a number of groups⁵⁾⁻⁷⁾ suggests the onset with increasing p_T of point-like constituent subprocesses. More recently the production of high p_T prompt photons, (i.e., not produced through the decay of intermediate states) as predicted by constituent hard scattering models⁸⁾⁻¹¹⁾ has been observed¹²⁾ in proton-proton collisions. It is clearly important to develop a consistent understanding of both hadron and prompt photon production and to have more detailed QCD predictions for comparison with the growing body of data emerging from FNAL and the CERN ISR. Further, an effort should be made to separate point-like constituent effects from the background of hadron-quark subprocesses which may not be negligible in the subasymptotic domain especially for hadron production. Jet production should be less sensitive to the background since the suppression due to the fragmenting of the point-like constituents is absent. The Constituent Interchange Model^{13),14)} (CIM) is an attempt to construct a representation for these "higher twist" effects in QCD.

Jones and Gunion¹⁵⁾ have argued that the 90° single π^0 and $\bar{p}$ spectra in the intermediate to high p_T region can be understood on the basis of a hard scattering expansion, in which quark and gluon constituent contributions dominate CIM subprocesses in the high p_T range. A similar transition was predicted⁹⁾ in the single-photon to pion production ratio. It should be noted, however, that these calculations neglect the scale violation effects characteristic of QCD.

We attempt in this work to provide a study of the role of both fundamental and "higher twist" QCD subprocesses in high p_T π^0 and γ production, with due attention to QCD scale violation effects and to confront this picture with recent ISR data. It is important to note that although the inclusion of scale violations is found to perceptibly modify the p_T behaviour of QCD cross-sections at fixed x_T ($\equiv 2p_T/\sqrt{s}$) and fixed s , it has only a small effect on CIM predictions. This is because the composite constituents in the CIM are assumed to be colour singlets

and hence do not radiate soft gluons. When these effects are properly taken into account we conclude that for large energies and $p_T \gg 10 \text{ GeV/c}$ the perturbative QCD picture alone is pertinent but that this is unlikely to be true at ISR energies for hadron triggers where "higher twist" contributions are important for all p_T values and are dominant for $p_T < 10 \text{ GeV/c}$. The sharp cross-over between CIM and QCD predicted at ISR energies from a scale invariant approach is no longer apparent because scale violating effects affect QCD much more strongly than CIM. Such "higher twist" effects are particularly needed to reproduce pion data at low p_T and this implies the presence of direct photon production by similar mechanisms. At ISR energies such photons are important at all p_T , and for a 90° photon-trigger their contribution is much larger than that of photons coming from perturbative QCD subprocesses, they also contribute significantly to the signal for unresolved π^0 production for $p_T \gtrsim 10 \text{ GeV}$. We further conclude that for perturbative QCD subprocesses at the ISR, photons radiated from a high p_T quark are as numerous as those produced directly at high p_T .

2. SINGLE π^0 AND PROMPT PHOTON PRODUCTION

The observed $N \approx 8$ behaviour of the invariant cross-section for inclusive π^0 production in high p_T proton-proton collisions:

$$E \frac{d^3\sigma}{dp^3} \Big|_{\theta_{cm}=90^\circ} (pp \rightarrow \pi^0 X) \sim \frac{(1-x_T)^9}{p_T^N} \quad (2.1)$$

(where $x_T = 2p_T/\sqrt{s}$ and $p_T \lesssim 8 \text{ GeV/c}$) is inconsistent with the presence of fundamental quark and gluon subprocesses alone, which predict $N \approx 4$ up to logarithmic scale violation effects. It has been shown¹⁶⁾ that the inclusion of constituent transverse momentum with off-shell kinematics is insufficient to resolve this discrepancy, and the presence of additional production mechanisms involving non-point like constituents is suggested. We shall employ the Constituent Interchange Model as a parametrization of such "higher twist" mechanisms complementary to the point-like constituent QCD subprocesses. Such additional terms provide a specific way of including some hadronic wave function effects in a well-defined calculational framework¹⁷⁾. Gaussian smearing of constituent transverse momentum may be introduced to crudely parametrize more complicated effects of the wave function, but it should not be wrongly assumed that this would be sufficient to account for all pertinent wave function properties. Higher twist effects are expected to arise naturally in any complete description of inclusive phenomena based on QCD.

We believe the inclusion of a CIM contribution to be as realistic an approach as is available in the absence of a more complete understanding of the QCD hadronic Fock state.

The production of prompt single photons directly from a hard scattering process has the important feature that the coupling of the photon to the quark constituents is well understood. The uncertainties associated with constituent fragmentation into hadrons are absent in contrast to the case of meson production and the predictions of the theory depend only on the nature of the relevant subprocesses and the constituent structure functions. Throughout this paper we employ the scale violating structure and fragmentation functions used in our earlier work¹⁶⁾.

The lowest order QCD subprocesses contributing to high p_T hadron production are shown in Fig. 1; the corresponding subprocess cross-sections may be found, for example, in Ref. 18). The CIM contributions in which a meson-like $q\bar{q}$ constituent participates in the subprocess, are shown in Fig. 2. Their cross-sections have been calculated in Ref. 14). These subprocesses involve the coupling α_M of the quark to the $q\bar{q}$ configuration. This parameter has been determined to within a factor of 2 in Ref. 14) by the use of fixed angle elastic scattering data to the value $\alpha_M \sim 2 \text{ GeV}^2$. In our calculations we shall adopt the value $\alpha_M = 1.3 \text{ GeV}^2$ which is determined by our fit to the inclusive π^0 data.

The QCD and CIM subprocesses for direct photon production are shown in Figs 3 and 4. Single photons can be produced promptly as participants in the hard subprocess or by quark bremsstrahlung, as shown in Figs 5 and 6^{*)}. In the former case, the trigger photon is unaccompanied by hadrons produced by constituent fragmentation or resonance decay.

We have performed calculations of the invariant cross-sections for inclusive π^0 and photon production at $\theta_{cm} = 90^\circ$ and ISR energies $\sqrt{s} = 31, 45, 52.7$ and 62.4 GeV. QCD scale violations are included and the cross-sections are evaluated using Monte Carlo integration techniques¹⁹⁾ rather than the simplified analytic expressions of Refs 9) and 14). We have included Gaussian constituent transverse momentum fluctuations with large $\langle k_T \rangle \sim 800 \text{ MeV/c}$. This value is consistent with that determined by Feynman et al. in Ref. 20) from a parametrization of the transverse momentum of Drell-Yan pairs and therefore represents the largest value compatible with such data. Such fluctuations increase the cross-section by at most a factor of two at $p_T \approx 2 \text{ GeV/c}$; their effect dies away rapidly with increasing p_T ¹⁶⁾. Meson production by resonance decay in the CIM contributions

*) The neglect of initial state bremsstrahlung is justified in Ref. 9).

has been simulated by using a z independent decay distribution such that the integrated ratio of total to promptly produced mesons is approximately two. This value is suggested by Blankenbecler et al. Ref. 14) and by Jones and Gunion Ref. 15). This choice is consistent with the average momentum accompanying a hadron trigger at high p_T measured by the BFS collaboration²¹⁾. In our calculation the ratio is less than two at low p_T being about 1.7 for π^0 production at $p_T = 3$ GeV/c and $\sqrt{s} = 52.7$ GeV. This result is in keeping with the findings of the BFS collaboration on the resonance decay contributions to single pion production in this region. Use of the structure functions of Refs 9) and 14) shows good agreement with the results of these works in the kinematic region ($x_T \rightarrow 1$) where the approximations employed there are expected to be valid. The results of our calculations are shown in Figs 7 to 10. We find that at ISR energies the yield of direct and bremsstrahlung photons produced by the QCD mechanisms illustrated in Figs 3 and 5 are comparable. This disagrees with the statement by Rückl et al.⁹⁾ that QCD bremsstrahlung contributes a maximum of 20% to the direct processes^{*)}. Our calculation includes scale violations and does not approximate the integrals and hence should give a more reliable prediction for this comparison.

At the lower energies ($\sqrt{s} = 31$ and 45 GeV) the CIM contributions to production are dominant over the whole p_T range. At the higher energies ($\sqrt{s} = 52.7$ and 62.4 GeV) CIM subprocesses dominate in the intermediate p_T range; the elementary QCD subprocesses become comparable for $p_T \gtrsim 8$ GeV/c although CIM contributions to prompt photon production are dominant at all four energies. In the calculations of Ref. 9) and 14), where scale violations were neglected and a constant value of the strong coupling constant $\alpha_s = 0.15$ chosen, the numerical importance of the fundamental QCD subprocesses was found to set in earlier. The relative magnitude of these to the "higher twist" terms is sensitive to scale violation which suppresses the lowest order QCD contributions more strongly than the CIM contributions as p_T is increased. Scale violations change the p_T^{-N} behaviour of the QCD single meson cross-section from $N = 4$ to $N = 6$ at fixed x_T . For the same reason, $Ed^3\sigma/dp^3$ also falls faster as a function of x_T for fixed p_T . These effects are much smaller for the CIM contributions which model the behaviour of the wave function when quark constituents of the same hadron recoil against each other with a large transverse momentum, $k_T \sim p_T$. The quarks are then to be considered as participants in the central scattering subprocess and

*) The difference may be traced to three factors. The running coupling constant $\alpha_s(p_T^2) \approx 0.3$ for a typical transverse momentum $p_T \approx 6$ GeV/c; the calculations of Ref. 9) assume a constant value $\alpha_s = 0.15$. At small $x_T (\approx 0.2)$ the approximations employed by Rückl et al. are poor, especially for bremsstrahlung production. The gluon distribution chosen by these authors is harder [$x G_g/p(x) \sim (1-x)^4$] than that of the parametrization we use [$x G \sim (1-x)^5$ at the reference momentum], with the consequence that the $qg \rightarrow q\gamma$ subprocess is more important with respect to the process $qq \rightarrow qq\gamma$ at high x_T than in our calculation.

not as constituents of the hadron. In this kinematic region which is complementary to the low $k_T(k_T \ll p_T)$ region relevant to perturbative QCD models, the dominant $q\bar{q}$ constituents are colour singlets and hence their structure functions are scale invariant. Further, there is no scale violating fragmentation in the CIM case. We have included the scale violation for the participating quark, but neglected the possibility of scale violations in the $q\bar{q}$ constituent wave function. In this model the photon invariant cross-section behaves as p_T^{-6} at fixed x_T modulo these small scale violating effects. This behaviour is to be compared with the p_T^{-8} behaviour at fixed x_T which would be suggested by a vector dominance model of photon production from such "higher twist" terms; the point-like coupling of the photon to the quark is absent. Scale violations modify more strongly the canonical p_T^{-4} behaviour of the QCD contributions. The x_T dependences at fixed p_T of the CIM and QCD cross-sections are comparable ($\sim (1 - x_T)^3$). Hence we expect similar p_T behaviours of the CIM and QCD photon contributions at fixed s ; indeed, Figs 7 to 10 show that above $p_T \sim 7$ GeV the two are roughly parallel. In summary, the importance of CIM terms persists into a higher transverse momentum range than scale invariant calculations would suggest.

ISR data on single π^0 production extending up to $p_T \approx 15$ GeV/c have recently become available⁵⁾⁻⁷⁾. It is important to note that at the top p_T range of the data, the two photons from π^0 decay are not resolved, so that the measured " π^0 " cross-section is actually that of π^0 plus real photons. This was not taken into account in the analysis of Jones and Gunion¹⁵⁾ where all the π^0 's were assumed to be resolved. It is evident from Figs 7-10 that photon contamination has a significant effect on the experimental π^0 cross-section. Figures 11-14 show the single π^0 data together with the results of our calculations for $\theta_{CM} = 90^\circ$ at various ISR energies. Single π^0 's are resolved in the $\sqrt{s} = 31$ GeV data of the A²BC experiment⁷⁾. Figure 11 compares these data with the QCD and CIM subprocess contributions to π^0 production. As pointed out earlier, the CIM subprocesses dominate at this energy and provide a satisfactory fit to the data. Similar conclusions hold for the $\sqrt{s} = 45$ GeV data shown in Fig. 12 where π^0 's are also resolved over the available p_T range. For comparison we also show, in the range $11 < p_T < 14$ GeV/c, the QCD and CIM contributions for unresolved π^0 's.

Figures 13 and 14 compare our calculation with the data at $\sqrt{s} = 52.7$ GeV and 62.4 GeV, taken from Refs 5)-7). π^0 's are resolved up to $p_T = 4.5$ GeV/c in the data of Clark et al.⁵⁾, and up to $p_T = 3.5$ GeV/c in the CCOR data⁶⁾. For $p_T \geq 7$ GeV/c the data taken from Ref. 7) are those obtained using the "normal geometry" of the A²BC apparatus for which π^0 decay photons were not

resolved in this region. For $p_T \gtrsim 7$ GeV/c we have correspondingly added our calculated γ and π^0 cross-sections to give the effective π^0 cross-section plotted in Figs 13 and 14. At all energies, the lowest order QCD terms alone are too low to account for the data; inclusion of CIM contributions in the hard scattering expansion provides good agreement. From Figs 11-14 it is to be noted that, for fixed s the QCD predictions run approximately parallel to the data especially for large s and $p_T > 10$ GeV/c. This reflects the fact that the p_T behaviour at fixed s of the QCD results matches that of the data. However, the over-all normalization constant required to bring the QCD predictions into agreement with the data is s dependent or alternatively at fixed x_T it is p_T dependent. The parallelism at fixed s between the QCD curves and the data is a fortuitous coincidence dependent on the detailed behaviour of the structure functions. The p_T behaviour at fixed x_T reflects the scaling properties of the subprocesses involved and modulo scaling violations it is independent of the detailed properties of the structure functions themselves.

Figure 15 shows the effective p_T power N of the π^0 invariant cross-section at fixed x_T , plotted against x_T , as extracted from the A²BC data. N is defined by⁷⁾

$$N = \log \left[\frac{E \frac{d^3\sigma}{dp^3} \Big|_2}{E \frac{d^3\sigma}{dp^3} \Big|_1} \right] / \log (\sqrt{s_2}/\sqrt{s_1})$$

$$p_T^1 = \frac{x_T \sqrt{s_1}}{2}, \quad p_T^2 = \frac{x_T \sqrt{s_2}}{2}$$

In Table 1 we show our predicted N values from comparing the curves at $\sqrt{s} = 31, 45, 52.7$ and 62.4 GeV. We give the results for some selected x_T values and we distinguish resolved π^0 produced from QCD alone or from QCD plus CIM and unresolved π^0 for large x_T . In the table we label the columns with the same symbol as the data to which they should be compared in Fig. 15. It can be seen that QCD alone does not give a good description of the data and it is only for $x_T \gtrsim 0.3$ that the values of N for unresolved π^0 for both QCD and QCD plus CIM contributions become similar (solid circles). This is because photon production in CIM is large in this region and is associated with the $N \sim 6$ behaviour which is similar to that expected from QCD with scaling violations. However, for $x_T = 0.3 - 0.4$ for resolved π^0 (open triangles) this $N \sim 6$ photon component is excluded and so we predict $N \sim 8$ from QCD plus CIM as the data show; QCD alone still predicts $N \sim 6$ at variance with the data. We conclude that the measured N values for $x_T \gtrsim 0.3$ for resolved and unresolved π^0 differ in a way that is compatible with a strong photon component in the unresolved π^0 signal

associated with the $N \sim 6$ behaviour at fixed x_T . Charged pion production experiments will be important in determining the size of the direct photon contribution to the π^0 yield, a measure of which is given by the difference

$$d\sigma(\gamma) = d\sigma(\pi^0) - \frac{1}{2} (d\sigma(\pi^+) + d\sigma(\pi^-))$$

To accentuate the angular dependence of the various subprocesses we shall consider in Section 3 the detection of single photons at $15^\circ < \theta_{tr} < 20^\circ$ and $\sqrt{s} = 62$ GeV; appropriate to a scheduled A²BC experiment at the ISR. Figure 16 shows the predicted contributions to $Ed^3\sigma/dp^3$ for π^0 and γ production as a function of p_T . Figure 17 shows the total γ and resolved π^0 invariant cross-sections.

In Fig. 18 we compare our calculated γ/π^0 ratio with the data⁷⁾. In Refs 10) and 11) the contributions of the point-like QCD subprocesses to prompt γ production (shown in Fig. 3) were used to predict γ/π^0 . The question of meson production was not addressed, and the γ/π^0 ratio was calculated by dividing the predicted QCD direct photon cross-section by the measured π^0 cross-section. The p_T behaviour of γ/π^0 cannot be reproduced by a consistent calculation of γ and π^0 production based on these subprocesses alone, since they do not account for the inclusive meson data. Here we are attempting a unified approach to both meson and prompt photon production; the curves shown in Fig. 18 are the ratio of our calculated γ and π^0 spectra. Multiplication of the data by a factor 0.85 ± 0.15 is necessary to obtain the fully integrated γ/π^0 ratio⁷⁾.

Figure 19 is a plot of γ/π^0 versus p_T for fixed $x_T = 0.15, 0.2$ and 0.25 . Lowest order QCD predicts a p_T independent ratio for fixed x_T , up to scale violating logarithms. Our model reproduces the trend in p_T , at both fixed x_T and s though the data fall somewhat below our theoretical curves. In Fig. 20 we give for comparison the calculated γ/π^0 ratio for $15^\circ < \theta_{tr} < 20^\circ$ and $\sqrt{s} = 62$ GeV.

We have calculated $\langle z \rangle = \langle p_{hadron}/p_{jet} \rangle$ as a function of p_T for π^0 and bremsstrahlung photon production in QCD, and for π^0 's produced by resonance decay in the CIM. Figure 21 shows our results for $\sqrt{s} = 31$ GeV and 62 GeV. It can be seen that $\langle z \rangle$ scales approximately in x_T though scale violations must be present. Because the fragmentation function $D_{\pi^0/q}(z)(\sim (1-z)/z)$ is softer than $D_{\gamma/q}(z)(\sim 1/z)$ we have generally $\langle z \rangle_{\pi^0, QCD} < \langle z \rangle_{\gamma, QCD}$. Moreover, since

the relevant CIM subprocesses fall faster in p_T than the corresponding QCD subprocesses and $D_{\pi^0/\text{RES}}(z) \sim D_{\gamma/q}(z)$, we find $\langle z \rangle_{\gamma, \text{QCD}} \lesssim \langle z \rangle_{\pi^0, \text{CIM}}$. Combining these results gives the weighted $\langle z \rangle$ for a detected pion:

$$\langle z \rangle = \frac{\sum_i \langle z \rangle_i \frac{E d^3 \sigma_i}{d p_T^2}}{\sum_i \frac{E d^3 \sigma_i}{d p_T^2}} \quad (2.2)$$

where i runs over all contributions. Related data²¹⁾ exist for π^+ and π^- production at $\sqrt{s} = 53$ GeV, extending up to $p_T \sim 5$ GeV/c; the average accompanying momentum $\langle p_x \rangle_{\text{ch}}$ carried by charged particles for rapidity $|y| < 1$ and azimuthal angle $|\phi| > 145^\circ$ was studied by the British-French-Scandinavian collaboration as a function of trigger p_T . Comparison of our results with these data is difficult because of their limited range in p_T and the large errors at the higher p_T values studied. We do not know how to estimate the effect of hadronic background unassociated with the jet. Assuming that neutrals carry 50% of the momentum, we estimate from the data that $\langle p_x \rangle \approx 800$ MeV for $p_T \sim 4$ GeV/c, which gives $0.83 < \langle z \rangle < 0.91$. This range corresponds to an uncertainty in the background of 0 - 400 MeV/c. From Fig. 21c and using the scaling behaviour of $\langle z \rangle$ we predict that from fundamental QCD subprocesses alone $\langle z \rangle \sim 0.68$ at $\sqrt{s} = 53$ GeV, $p_T = 4$ GeV/c, in disagreement with the estimate made above. With CIM processes present we calculate that $\langle z \rangle \sim 0.89$ in agreement with the value estimated above from the data. The production of prompt mesons (i.e., with no accompanying particles), as exemplified in the CIM, is indicated by these data. If such behaviour is to be parametrized by a fragmentation function for quark into pion instead, then we conclude that $D_{\pi^0/q}(z) \neq 0$ as $z \rightarrow 1$.

3. AWAY-SIDE ANGULAR DISTRIBUTIONS

In order to further distinguish the various subprocesses contributing to high p_T phenomena, in this section we study particle production away from $\theta_{\text{cm}} = 90^\circ$ and examine the angular variation of the away-side jet balancing the transverse momentum of the trigger. We shall compare single photon production at 90° and in the range 15° - 20° .

The away-side jet balancing the photon is predominantly due to a gluon, an up or a down quark in the QCD subprocesses of Figs 3 and 5. A quark balancing a bremsstrahlung photon may or may not be correlated in flavour with the quark emitting the photon. The subprocess in which it is not is represented by Fig. 5a, where the photon is emitted after a quark-quark scattering. The away-side particle will be an up or a down quark with frequency proportional to the

probabilities of the proton containing quarks of these flavours, i.e., approximately 2:1. In the other quark recoil subprocesses (Figs 5b, 5f, 5g) the away-side quark is four times more likely to be up than down since the ratio of up-to down quark charges is two. The production of a gluon jet recoiling against a radiated photon is dominated by Fig. 5c. An indication that this process is present will be evidence for the existence of non-Abelian trigluon couplings.

Prompt photon production is associated with either a recoiling quark or gluon, as illustrated in Fig. 3. The photon couples to the recoiling quark. We expect a dominance of recoiling up over down quark, an enhancement due to the charges and to the predominance of the up-quark distribution in the proton. The contribution of the subprocess Fig. 3c is small in pp collisions since it involves sea antiquarks as constituents. Thus the recoil of a gluon against a high p_T photon is dominated by Fig. 5c, a subprocess of particular interest since its magnitude depends on the strength of the trigluon coupling. Since the high p_T photon has been produced by bremsstrahlung in this subprocess it will be accompanied by low p_T hadrons on the trigger side. Data on charge correlations with and without particles on the same side as the trigger will serve to further distinguish the subprocesses involved.

The recoiling jet for photons produced by the CIM mechanism is expected to be dominated by the up quark.

There are two factors governing the relative magnitude of the individual subprocesses: the angular dependences of the subprocess cross-sections and the structure functions of the constituents involved. Some elucidation of the role played by these factors is useful.

Consider the subprocess $a + b \rightarrow c + d$ where c is the trigger particle detected at c.m. angle θ_{tr} with respect to the collision axis and with transverse momentum p_T . The light cone variables x_a, x_b of the constituents a and b are related by

$$x_a = \frac{x_R x_b C_+}{2x_b - x_R C_-} \quad \text{or} \quad x_b = \frac{x_R x_a C_-}{2x_a - x_R C_+} \quad (3.1)$$

where $c_{\pm} = 1 \pm \cos\theta_{tr}$, and $x_R = x_T/\sin\theta_{tr}$. If a and b have no intrinsic transverse momentum the angle θ_{aw} of the away-side jet is determined by

$$\cot \theta_{aw} = \frac{(x_a - x_b) z}{x_T} - \cot \theta_{tr} \quad (3.2)$$

where z is the momentum fraction of the trigger particle $z = p_{tr}/p_c$. It is a good approximation to take $z \approx 1$ because of the trigger bias effect⁴⁾, and for illustration we choose $x_T = 0.1$, corresponding to $p_T \approx 3$ GeV/c for $\sqrt{s} = 63$ GeV.

The subprocess Mandelstam variables are

$$\hat{s} = x_a x_b s, \quad \hat{t} = -x_a x_R c - \frac{s}{2}, \quad \hat{u} = -x_b x_R c + \frac{s}{2} \quad (3.3)$$

For small θ_{tr} , the minimum value of x_a is $x_a \approx x_R$, so that for $\theta_{tr} = 15^\circ$, $\sqrt{s} = 63$ GeV, $x_T = 0.1$, we have $|\hat{t}_{min}| \approx x_R^2(c-s)/2 \approx 10$ GeV² and perturbative calculations are meaningful.

The cross-section for the inclusive process $A + B \rightarrow c + x$ is given by

$$E \frac{d^3\sigma}{dp_c^3} = \sum_{a,b} \int G_{a/A}(x_a) G_{b/B}(x_b) \frac{\hat{s}}{\pi} \frac{d\sigma}{d\hat{t}} \delta(\hat{s} + \hat{t} + \hat{u}) dx_a dx_b \quad (3.4)$$

where $d\sigma/d\hat{t}$ is the differential cross-section for the $a + b \rightarrow c + d$ subprocess and $G_{a/A}(x_a)$ is the distribution of constituent a within the incoming hadron A .

In order to illustrate the roles played by the factors mentioned above and to generate a feeling for the behaviour of the angular distributions presented below, we consider two away-side angles: $\theta_{aw} = 15^\circ$ for which $\hat{s} = 4p_T^2$ and $\theta_{aw} = 165^\circ$ for which $\hat{s} = 4p_T^2/\sin^2\theta_{tr}$ and $c + d$ emerge in a back-to-back configuration. It might be expected that the cross-section in this latter case would be small because $\hat{s}$ is large. This is not generally true, as we demonstrate below. We can use Eqs (3.1) and (3.3) to rewrite Eq. (3.4) as

$$E \frac{d^3\sigma}{dp_c^3} = \frac{2}{\pi} \sum_{a,b} \int G_{a/A}(x_a) G_{b/B}(x_b) \frac{\hat{s}}{s(2x_a - x_R c_+)} \frac{d\sigma}{d\hat{t}} dx_a \quad (3.5)$$

For the case $\theta_{aw} = \theta_{tr}$, Eqs (3.1) and (3.2) give $x_a = x_R c_+$, $x_b = x_R c_-$ and

$$\frac{dx_a}{d\theta_{aw}} = \frac{x_R c_+}{2 \sin \theta_{tr}} \quad (3.6)$$

so that Eq. (3.5) becomes

$$E \frac{d^3\sigma}{dp_c^2 d\theta_{aw}} = \frac{1}{\pi} \sum_{a,b} G_{a/A}(x_{R+}) G_{b/B}(x_{R-}) x_R^2 \sin \theta_{tr} \left. \frac{d\sigma}{d\hat{t}} \right|_{\theta_{aw}=\theta_{tr}} \quad (3.7)$$

For the case $\theta_{aw} = -\theta_{tr}$, we have $x_a = x_b = x_R$ and

$$\frac{dx_a}{d\theta_{aw}} = \frac{x_R c_-}{2 \sin \theta_{tr}} \quad (3.8)$$

so that

$$E \frac{d^3\sigma}{dp_c^2 d\theta_{aw}} = \frac{1}{\pi} \sum_{a,b} G_{a/A}(x_R) G_{b/B}(x_R) \frac{x_R^2}{\sin \theta_{tr}} \left. \frac{d\sigma}{d\hat{t}} \right|_{\theta_{aw}=-\theta_{tr}} \quad (3.9)$$

Then

$$R \equiv \frac{d\sigma(\theta_{aw}=-\theta_{tr})}{d\sigma(\theta_{aw}=\theta_{tr})} = \frac{1}{\sin^2 \theta_{tr}} \frac{\sum_{a,b} G_{a/A}(x_R) G_{b/B}(x_R) \left. \frac{d\sigma}{d\hat{t}} \right|_{\theta_{aw}=-\theta_{tr}}}{\sum_{a,b} G_{a/A}(x_{R+}) G_{b/B}(x_{R-}) \left. \frac{d\sigma}{d\hat{t}} \right|_{\theta_{aw}=\theta_{tr}}} \quad (3.10)$$

For illustration we choose here the structure functions:

$$G_{u/p}(x), G_{d/p}(x) \sim \frac{(1-x)^3}{x}; \quad G_{M/p}(x), G_{g/p}(x) \sim \frac{(1-x)^5}{x} \quad (3.11)$$

For the case $a = b = \text{quark}$,

$$R \approx \frac{2 \left. \frac{d\sigma}{d\hat{t}} \right|_{\theta_{aw}=-\theta_{tr}}}{\left. \frac{d\sigma}{d\hat{t}} \right|_{\theta_{aw}=\theta_{tr}}} \quad (3.12)$$

and

$$\frac{d\sigma}{d\hat{t}} \propto \frac{\hat{s}^2 + \hat{u}^2}{\hat{s}^2 \hat{t}^2} \quad (3.13)$$

With the values chosen above ($\theta_{tr} = 15^\circ$, $x_T = 0.1$), we have $\hat{f}_+/\hat{f}_- = c_+ \approx 2$, $\hat{u}_+/\hat{u}_- = c_- \approx 0.04$, $\hat{s}_+/\hat{s}_- = c_+c_- \approx 0.1$. Equations (3.12) and (3.13) then give $R(qq \rightarrow qq\gamma) \approx 13$.

In the case of quark-gluon scattering, it is clear from Eqs (3.9) and (3.11) that for $\theta_{aw} = \theta_{tr}$, the advantageous configuration is $a = \text{quark}$, $b = \text{gluon}$, since $x_a = x_R^{c_+}$, $x_b = x_R^{c_-}$. In this case

$$R \approx 0.77 \frac{d\sigma}{d\hat{t}} \Big|_{\theta_{aw} = -\theta_{tr}} / \frac{d\sigma}{d\hat{t}} \Big|_{\theta_{aw} = \theta_{tr}} \quad (3.14)$$

and

$$\frac{d\sigma}{d\hat{t}} (qg \rightarrow qg\gamma) \propto \frac{\hat{u}^2 + \hat{s}^2}{\hat{s}^2 \hat{t}^2} - \frac{4}{9} \cdot \frac{\hat{u}^2 + \hat{s}^2}{\hat{s}^3 \hat{u}} \quad (3.15)$$

$$\frac{d\sigma}{d\hat{t}} (qg \rightarrow \gamma q) \propto - \frac{(\hat{s}^2 + \hat{t}^2)}{\hat{s}^3 \hat{t}} \quad (3.16)$$

which give $R(qg \rightarrow qq\gamma) \approx 6$, $R(qg \rightarrow \gamma q) \approx 0.1$,

For the CIM case, $a = \text{quark}$, $b = \text{meson}$

$$R \approx 0.77 \frac{d\sigma}{d\hat{t}} \Big|_{\theta_{aw} = -\theta_{tr}} / \frac{d\sigma}{d\hat{t}} \Big|_{\theta_{aw} = \theta_{tr}} \quad (3.17)$$

and⁹⁾

$$\frac{d\sigma}{d\hat{t}} (qM \rightarrow \gamma q') \propto \frac{\hat{s}^2 + \hat{t}^2}{\hat{s}^2 \hat{u}} \left(\frac{e_{\bar{q}}}{\hat{t}} - \frac{e_{q'}}{\hat{s}} \right)^2 \quad (3.18)$$

where e_q denotes quark charge, so that $R(qM \rightarrow \gamma q) \approx 0.6$.

These rough estimates are only expected to be valid within a factor of two; however, the effects of the structure functions and subprocess angular dependences are well illustrated. These results are reflected in Figs 22 and 23 where the angular distributions of quark and gluon jets recoiling against a 15° trigger

photon are shown for $\sqrt{s} = 63 \text{ GeV}^2$ and $p_T = 3,4 \text{ GeV/c}$. The cross-sections for bremsstrahlung photons recoiling against up-quark and gluon jets are higher for the configuration $\theta_{aw} = -\theta_{tr}$ than for $\theta_{aw} = \theta_{tr}$ in roughly the ratios estimated above. The distribution for a direct photon recoiling against an up-quark jet has the opposite behaviour; that for a photon produced by the CIM mechanism, balanced by an up-quark jet, is approximately flat. It should thus be possible to distinguish contributing subprocesses by studying the away-side angular distributions with a 15° photon trigger. That this is not the case with a 90° photon trigger can be seen from Figs 24 and 25. Moreover unlike the $\theta_{tr} = 90^\circ$ case, for $\theta_{tr} = 15^\circ$ the CIM contribution is suppressed and the QCD subprocess Fig. 5c dominates over most of the away-side angular range.

The presence of the subprocess Fig. 5c involving the QCD trigluon coupling may be inferred from a study of the angular distribution of the away-side mean charge as shown in Fig. 26. Throughout the range $60^\circ < \theta_{aw} < 120^\circ$ the mean charge $\langle Q \rangle \approx 0.25$, in the absence of the non-Abelian coupling subprocess $\langle Q \rangle \approx 0.45$. Fundamental QCD alone (no CIM subprocesses) predicts $\langle Q \rangle \approx 0.15$; $\langle Q \rangle \approx 0.4$ if the trigluon coupling is absent. A backward dip in the mean charge distribution is in every case more pronounced when CIM contributions are included. The detection of this structure would provide additional evidence for the presence of higher twist contributions of the nature discussed in this paper.

Similar analysis at $\theta_{tr} = 90^\circ$ using the results of Fig 24 and 25 gives the $\langle Q \rangle$ predictions shown in Fig. 27. The signal for the trigluon vertex is very weak when CIM is present [curves (a) and (c)]. With QCD subprocesses alone it is only 60% of the corresponding signal at $\theta_{tr} = 15^\circ$. Moreover, the substantially lower $\langle Q \rangle$ at $\theta_{tr} = 15^\circ$ would be more difficult to reconcile with the absence of gluon recoil than the higher $\langle Q \rangle$ at $\theta_{tr} = 90^\circ$. Nothing is gained by increasing p_T since the CIM contribution becomes proportionately larger while the contribution of the gluon recoiling against a bremsstrahlung photon decreases - a trend evident from Fig. 24.

4. CONCLUSIONS

The fundamental QCD hard scattering subprocesses do not account for the observed π^0 spectrum. The $N \approx 8$ behaviour of the intermediate p_T single π^0 invariant cross-section indicates the presence of additional non-point-like subprocesses. Those mechanisms which give rise to copious pion and vector meson production must be expected also to contribute to high p_T prompt photon production. The incorporation of such "higher twist" effects as parametrized

by the Constituent Interchange Model leads to a successful picture of the π^0 and γ data in the ISR range. In particular the behaviour of $E d^3\sigma/dp^3(pp \rightarrow \pi^0 x)$ in p_T is reproduced both for fixed x_T and for fixed s , when photon contamination is taken into account. At fixed x_T this cross-section behaves like p_T^{-N} where $N \sim 8$ for $p_T \lesssim 6$ GeV/c and $N \sim 6$ for $p_T \gtrsim 10$ GeV/c which is observed in the data for unresolved inclusive π^0 . The value of N is predicted to be higher for resolved π^0 as is observed by the "super-retracted" experimental configuration of Ref. 7). This is because the dominant contribution of "higher twist" photons associated with $N \sim 6$ has been excluded leaving a mixture of contributions with larger effective N .

Disentangling the subprocesses contributing to high p_T scattering requires more detailed experiments. Correlation and angular distribution studies will be very useful here. In prompt photon production, where QCD contributions are not suppressed by hadronic fragmentation, the CIM background is damped at trigger angles away from 90° . We have suggested that the strength of the QCD trigluon coupling may be studied by means of the average charge distribution of the away-side jet. Predictions for hadronic correlation experiments will be made in a separate work²²⁾.

On the theoretical side, much work remains to be done on the understanding of the "higher twist" sector of Quantum Chromodynamics.

ACKNOWLEDGEMENTS

We thank M. Albrow, M. Jacob and D. Lissauer for useful discussions. One of us (P.S.) thanks J. Prentki and the CERN Theory Division for their hospitality. Our numerical calculations were performed using VEGAS, a Monte Carlo multidimensional integration program developed by G.P. Lepage¹⁹⁾.

Table 1

The p_T power N defined for fixed x_T by $Ed^3\sigma/dp^3(pp \rightarrow Mx) \sim p_T^{-N}$. Results for both resolved and unresolved π^0 are given for various values of x_T . The two values of $\sqrt{s}$ used to determine N are given at the head of each column as is the symbol labelling the data points on Fig. 15 with which these numbers should be compared.

	π^0 resolved				π^0 unresolved	
	QCD		QCD + CIM		QCD	QCD + CIM
x_T	45/62 x	53/62 o	45/62 x	53/62 o	53/62	
0.15	6.2	5.8	8.6	8.0		
0.2	5.8	5.8	7.6	6.7		
0.25	5.5	5.4	7.1	6.7		
	31/45 Δ		31/45 Δ		•	•
0.3	5.4		8.5		5.5	5.8
0.4	6.2		7.5		5.5	5.7
0.5					5.3	5.5

FIGURE CAPTIONS

- Fig. 1 : Lowest order QCD subprocesses contributing to high p_T hadron production. Solid lines represent quarks (antiquarks); wavy lines represent gluons.
- Fig. 2 : CIM "higher twist" subprocesses contributing to high p_T meson production.
- Fig. 3 : Lowest order QCD subprocesses contributing to high p_T direct photon production.
- Fig. 4 : CIM "higher twist" subprocesses contributing to high p_T direct photon production.
- Fig. 5 : Lowest order QCD subprocesses contributing to high p_T bremsstrahlung photon production.
- Fig. 6 : CIM "higher twist" subprocesses contributing to high p_T bremsstrahlung photon production.
- Fig. 7 : Calculated QCD and CIM contributions to the invariant cross-sections for π^0 and γ production at $\theta_{cm} = 90^\circ$, $\sqrt{s} = 31$ GeV. (a) π^0 QCD; (b) direct γ QCD; (c) brems γ QCD; (d) π^0 CIM; (e) γ CIM.
- Fig. 8 : As in Fig. 7, for $\sqrt{s} = 45$ GeV.
- Fig. 9 : As in Fig. 7, for $\sqrt{s} = 52.7$ GeV.
- Fig. 10 : As in Fig. 7, for $\sqrt{s} = 62.4$ GeV.
- Fig. 11 : π^0 invariant cross-section versus p_T for $\sqrt{s} = 31$ GeV, $\theta_{CM} = 90^\circ$; data from Ref. 7). The dashed curve is the QCD contribution; the solid curve is the total of QCD + CIM contributions.
- Fig. 12 : As in Fig. 11, for $\sqrt{s} = 45$ GeV. Below $p_T = 10$ GeV/c, π^0 's are resolved; above the cross-sections for resolved π^0 and γ are summed.

- Fig. 13 : As in Fig. 12, for $\sqrt{s} = 52.7$ GeV, but summing π^0 and γ contributions for $p_T > 7$ GeV.
- Fig. 14 : As in Fig. 12, for $\sqrt{s} = 62.4$ GeV, but summing π^0 and γ contributions for $p_T > 7$ GeV.
- Fig. 15 : Effective p_T power, N , of the π^0 invariant cross-section as a function of x_T , taken from Ref. 7).
- Fig. 16 : Calculated QCD and CIM contributions to the invariant cross-sections for π^0 and γ production at $15^\circ < \theta_{tr} < 20^\circ$, $\sqrt{s} = 63$ GeV.
- Fig. 17 : Total γ and resolved π^0 cross-sections for $15^\circ < \theta_{tr} < 20^\circ$, $\sqrt{s} = 63$ GeV.
- Fig. 18 : Calculated γ/π^0 ratio plotted against p_T for $\theta_{cm} = 90^\circ$, $\sqrt{s} = 31, 45$ and 63 GeV/c. The data are from Ref. 7).
- Fig. 19 : Calculated γ/π^0 ratio plotted against p_T for fixed $x_T = 0.15, 0.2$ and 0.25 . The data are taken from Ref. 7).
- Fig. 20 : Calculated γ/π^0 ratio plotted against p_T for $\sqrt{s} = 63$ GeV, $15^\circ < \theta_{tr} < 20^\circ$.
- Fig. 21 : Calculated $\langle z \rangle$ as a function of p_T for $\sqrt{s} = 31$ and 63 GeV,
 (a) for π^0 's from decay of resonances produced by the CIM mechanism.
 (b) for bremsstrahlung photons produced by QCD subprocesses;
 (c) for π^0 's produced by QCD subprocesses.
- Fig. 22 : Angular distributions of away-side up-quark and gluon jets recoiling against prompt photons produced at $15^\circ < \theta_{tr} < 20^\circ$, $\sqrt{s} = 63$ GeV; $p_T = 3, 4$ GeV/c.
 (1) direct γ, G ; (2) direct γ, u ; (3) brems γ, G ;
 (4) brems γ, u ; (5) CIM γ, u .
- Fig. 23 : Angular distribution of away-side down-quark jets recoiling against direct photons produced at $15^\circ < \theta_{tr} < 20^\circ$, $\sqrt{s} = 63$ GeV; $p_T = 3, 4$ GeV/c.
 (1) brems γ, d ; (2) direct γ, d ; (3) CIM γ, d .

Fig. 24 : As in Fig. 22, for $\theta_{tr} = 90^\circ$.

Fig. 25 : As in Fig. 23, for $\theta_{tr} = 90^\circ$.

Fig. 26 : Mean charge (in units of 1/3) recoiling against a prompt photon plotted against the away-side angle, θ_{aw} for $\sqrt{s} = 63$ GeV, $15^\circ < \theta_{tr} < 20^\circ$ and $p_T = 3, 4$ GeV/c.

(a) CIM plus QCD contributions.

(b) QCD contributions alone.

(c) CIM plus QCD but no $3g$ coupling.

(d) QCD alone with no $3g$ coupling.

Fig. 27 : As for Fig. 26 but $\theta_{tr} = 90^\circ$.

REFERENCES

- 1) For a recent review see
J. Ellis and C.T. Sachrajda, in Proc. of the 1979 Cargèse Summer Institute on Quarks and Leptons.
- 2) H.D. Politzer, Phys. Rev. Letters 30 (1973) 1346;
D.J. Gross and F.A. Wilczek, Phys. Rev. Letters 30 (1973) 1343.
- 3) D. Amati, R. Petronzio and G. Veneziano, Nucl. Phys. B146 (1978) 29;
G. Sterman and S. Libby, Phys. Rev. D18 (1978) 3252, 4737;
R.K. Ellis, H. Georgi, M. Machacek, H. Politzer and G.G. Ross, Nucl. Phys. B152 (1979) 285.
- 4) M. Jacob and P.V. Landshoff, Phys. Rep. 48 (1978) 285.
- 5) A.G. Clark et al., Phys. Letters 74B (1978) 267; Nucl. Phys. B142 (1978) 196.
- 6) A.L.S. Angelis et al., Phys. Letters 79B (1978) 505.
- 7) C. Kourkouvelis et al., CERN report (1980) EP/80-07 Revised.
- 8) H. Fritzsch and P. Minkowski, Phys. Letters 69B (1977) 316.
- 9) R. Rückl, S.J. Brodsky and J.F. Gunion, Phys. Rev. D18 (1979) 2469.
- 10) F. Halzen and D. Scott, Wisconsin report C00-881-102 (1979).
- 11) A.P. Contogouris, S. Papadopoulos and M. Hongoh, Phys. Rev. D19 (1979) 2607.
- 12) M. Diakonou et al., CERN report EP/80-02 (1980), to be published in Phys. Letters B.
- 13) P.V. Landshoff and J.C. Polkinghorne, Phys. Rev. D8 (1973) 927; D10 (1974) 891.
- 14) R. Blankenbecler, S.J. Brodsky and J.F. Gunion, Phys. Rev. D18 (1978) 900.
- 15) D. Jones and J.F. Gunion, Phys. Rev. D19 (1979) 867.
- 16) R.R. Horgan and P.N. Scharbach, Phys. Letters 81B (1979) 215.
- 17) W.E. Caswell, R.R. Horgan and S.J. Brodsky, Phys. Rev. D18 (1978) 2415.
- 18) B.L. Combridge, J. Kripfganz and J. Ranft, Phys. Letters 70B (1977) 234.
- 19) G.P. Lepage, J. Comput. Phys. 27 (1978) 192.
- 20) R.P. Feynman et al., Phys. Rev. D18 (1978) 3320.
- 21) M.G. Albrow et al., Nucl. Phys. B145 (1978) 305.
- 22) R.R. Horgan and P.N. Scharbach, work in preparation.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 18
(Cont.)

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

46